Micro and Smart Systems
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Lecture - 33
Op-Amp Circuits and Signal conditioning for Microsystems Devices

Today, we will have presentation on Op-Amp circuits and signal conditioning for Microsystems devices. So we will actually continue from where we left in our previous discussion on the amplifier little bit.

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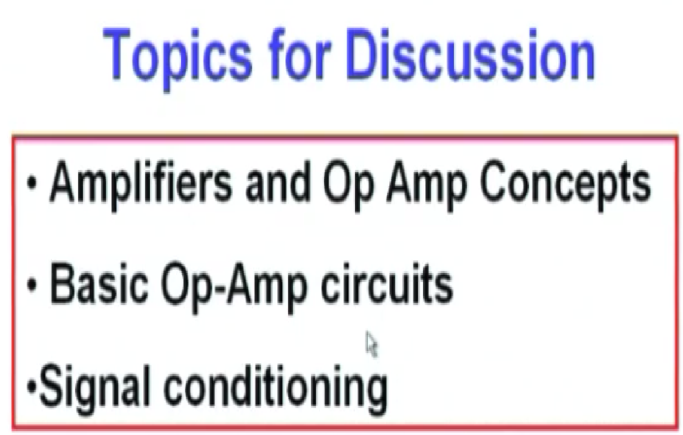

So today we will go through that portion of the amplifier, then op-amp concepts, basic op-amp circuits and signal conditioning circuits.

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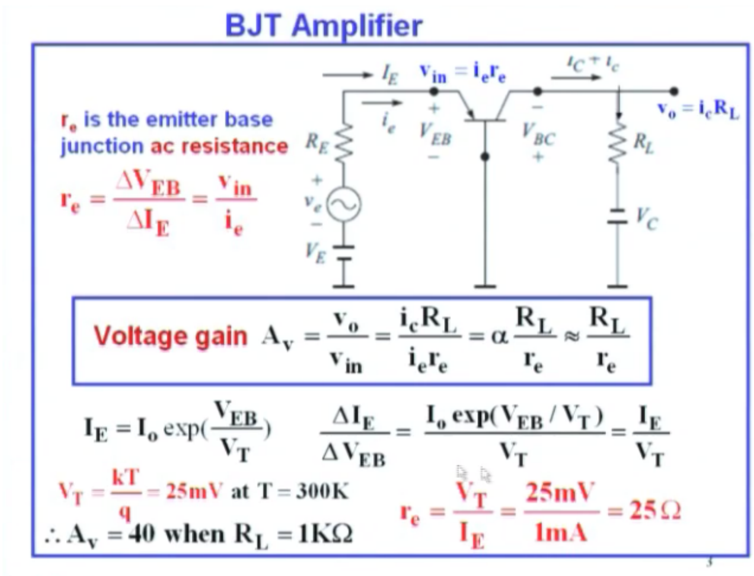

So we saw last time. I just had quickly gone through this portion of BJT common base amplifier circuit. Here, what I would like to point out is there is DC as well as AC. The DCVE is connected to the emitter lead through a resistance RE so that the emitted current is fixed by this loop = VE divided by RE approximately. Strictly speaking it is VE – VEB divided by RE, but VE will be large compared to VEB, because VEB is the order of 0.65 volts.

So IE is fixed once fixed VE and RE. That is biasing. Once I fix IE, if the current is reverse biased. Whatever IE flows through emitter will reach the collector. So DC current IE, if it is 1 milliampere, connector current IC will be 1 milliampere DC. Now what we are talking of is, this bias VE and VC are applied so that the transistor is operating the active region, so that emitter based junction is forward biased pumping a current of I DC = 1 milliampere or whatever you want, set by this voltage and resistance and correspondingly the collector current, if it is 1 milliampere, that is also 1 milliampere.

Now R = 1K, 1 kilo ohm. If 1 milliampere flows through this circuit, the drop is 1 volt. So if this is 4 volt, the voltage VBC will be actually 4 volts – 1 volt, 3 volts. So there will be a reverse bias of 3 volts. Suppose the current is 2 milliamperes, then the drop will be 2 volts, so 4 volts – 2 volts, 2 volts will be reverse bias. Now what we do is, to use it as an amplifier for small signal purposes. I apply voltage ve in series with this. This is not the way it is applied.

But I am showing it schematically like this. So VE sets in a current ie, which is AC current and that ie, when it is closed develops a voltage V in that is AC voltage across the emitter and the base. Now how much voltage flows through that depends upon how much current you pump in. If I pump in some small signal current IE, the drop Vin will be = IE in RE where RE is the junction resistance of the forward bias diode.

It is actually incremental resistance or small signal resistance that we will see how to find out. This RE will actually be small. So input voltage Vin will be = IE*RE. Now output current Ic will be almost same as IE, actually it is alpha times IE, alpha is the current gain. So if this I will be much smaller compared to the DC current. If DC current is 1 milliampere, this may be microampere of that range. So IC also is the same.

Or at the most if it is 1 milliampere, this may be 1/4th of a milliampere. Collected current also will be 1/4th of a milliampere. So now ie is the AC current, ic will be the AC collector current, which will be same as the ie. So this is resulting in AC voltage drop across the RL. So AC voltage drop across RL will be IC times RL. AC voltage input Vin = ie x re and IC/IE is alpha, so therefore the voltage gain V0/Vin = alpha x Rl/Ri.

Now what is Re, when I said Rl let it be 1 K ohms. Now re, e is actually the incremental resistance of this forward bias junction, which is actually delta Veb/delta E or delta Veb is small signal voltage that is Vin, delta ie is small signal current that is ie. Now, how this will be, we find out like this. DC current IE is I0 E to the power of Ve/Vt. Delta E/delta V = 1/Vt x I0 E to the power of Ve/Vt. That is delta IE/delta VE will be IE/Vt and what is Vt.

Vt is actually Kt/Q. K is the Boltzmann constant, t is the temperature in degree Kelvin, Q is electronic charge. At room temperature, this turns out to be about 25.8 millivolts. I put it as 25 millivolt for simplicity at 300 degree Kelvin. So Re is Vt/Ie because delta E/delta Vb is Ie/Vt. Delta Vb/delta E as seen here is Re. Vt/Ie, supposing the Vt is 25 millivolts as calculated here. If DC current is 1 milliampere, Re is 25 millivolts/1 milliampere that is 25 ohms.

If you have 1 milliampere, it is a current flowing through the connector. Incremental resistance is actually 25 ohms because DC current is also 1 milliampere. So that is 25 ohms. So the voltage gain now will be Rl/Re that 1 kilo ohm/25 ohms, that is 40. So you will get again 40 if the DC current is set at 1 milliampere. Suppose the DC current is 2 milliampere, what happens. The DC current is 2 milliampere. The DC drop across this increases by 2 volts.

So if these are 4 volts, the voltage across this will be 2 volts DC, but this ensures that, even though this is reduced from 2 volts, this junction is reverse biased. So transistor is still in the active region. So Ic will be = Ie practically and ic will be = ie, therefore the same equation holds good in this case. The only difference is since the current is 2 milliampere DC, you Re will be 25 divided by 2 milliampere that is 12.5 ohms, which would make the voltage gain = 1000 divided by 12.5 that is 80.

So what we say is, if I choose larger and larger Ie, the gain will go up because Re keeps on reducing, but there is an upper limit on this. Let us see how much is that. If I go on increasing the Ie.

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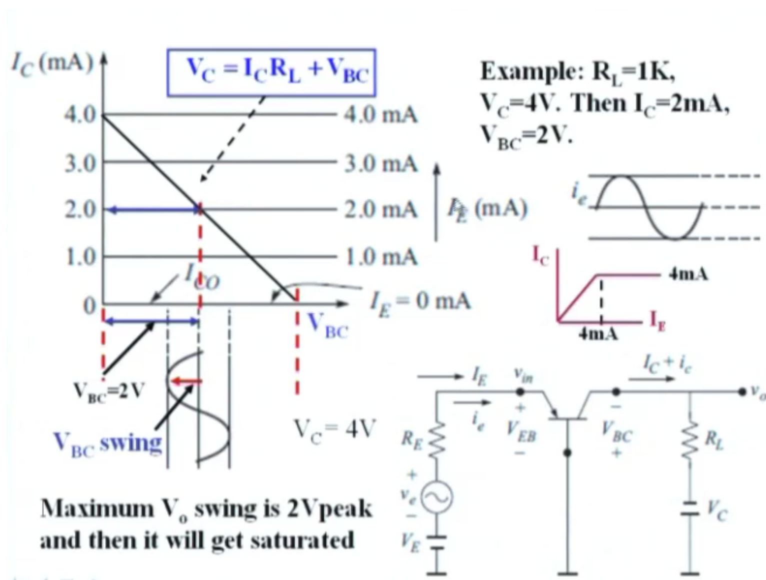

See here, this is the output characteristics of the transistor. For each Ie 1 milliampere, connector current is 1 milliampere and so long as the reverse biopsy is present, current is constant, 1, 2, 3, 4. This is the output characteristic, which we solved. Now, the current is also decided by, when applied voltage 4 volts, the voltage VBC will depend upon how much is the current and how much is the resistance. That is related by EC = IC times Rl plus VBC.

So you can see, this is equation of a straight line IC versus VC, if I plot, so we can see 1 IC = 0, VC = VBC. VBC is on the x axis, that is = Vc 4 volts. When VBC = 0, if I keep on increasing the current, 4 volts, supposing it is 2 milliampere, 2 volts drop, 3 milliampere, 3 volts drop, 4 milliampere 4 volts drop, applied voltage 4 volts, this will be = 0. So we can see that when this is VBC = 0, VC = IC x Rl or Vc if it is 4 volts, Rl is 1 K, this is 4 milliamperes. 4 volts by 1 K is 4 milliamperes.

So what we say is in this type of operation, I can keep on increasing this particular current through this transistor in order to get better and better gain because it is Vt by Ie. I can keep on increasing till the emitter current is 4 milliamperes. Once it becomes 4 milliamperes, VBC becomes = 0 if I go beyond that point, the collector base junction will get forward biased. So once it gets forward biased, collector current will not increase proportional to emitter current.

So Ic will saturate at that 4 milliamperes. So therefore there is no point in increasing the current beyond 4 milliamperes. So where there is 4 milliamperes, the output voltage peak will be actually = 1 K*4 milliampere, 4 volts, so that will maximizing of the output voltage will come down to 4 volts. Now on the other side, if Ic = 0, that will be 4 volts. If Ic = 0, there is no current occurrence, DC current at all.

If there is no DC current, the output voltage will be clip-clamped on to this VBC itself. It will not change beyond that point. So therefore, we will have clipping between 2 volts peak and 0 volts on the other side. So the sink in between from 2 to 4 and 2 to 0, 4 volts maximum peak to peak, you will get in this device, so what I am trying to point out is the sinusoidal operation of the signal will stop when the amplitude of the sinusoidal signal reaches close to the supply voltage.

Or an amplitude reaches close to that 0 voltage point. If there are 2 supply on both ends of the amplifier, then you will have + and – upper limits, in this case, you have got + and 0, 2, and 4 that is all. Now let us go on to this what I wanted to point out last time finish up.

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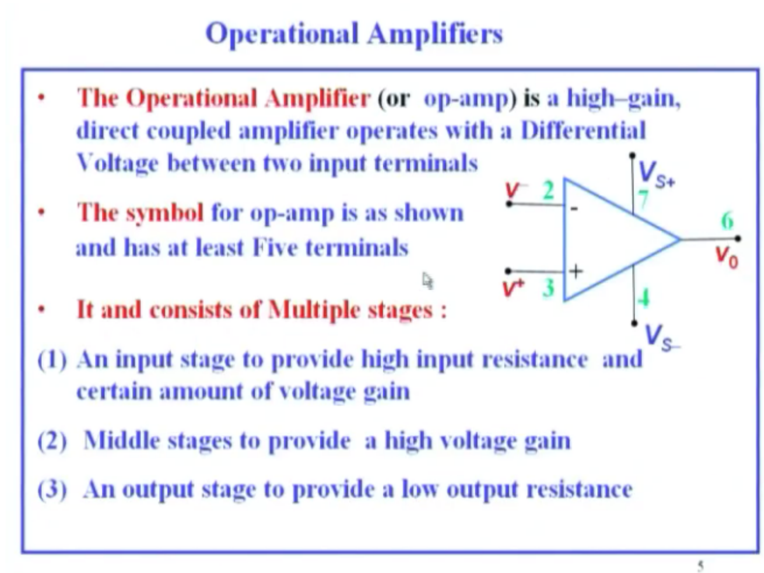

Let us take a look at this operational amplifier. This is a very popular device. Operational amplified is a high gain direct coupled amplifier, which operates with the differential voltage between 2 input terminals. Whatever is the difference voltage, it gets amplified. If there is a common voltage, then a difference voltage 0 at that point, if you apply even the voltage between the 2 same, output will ideally be = 0.

The symbol for op amp is given like this. It has multiple stages. Input stage, it provides high input resistance, so that the current drawn is minimum. We have discussed this aspect middle stages to provide high voltage gain, so input stage, middle stage for high voltage gain, output stage to give low resistance. Now let us just take a look at the op amp terminals.

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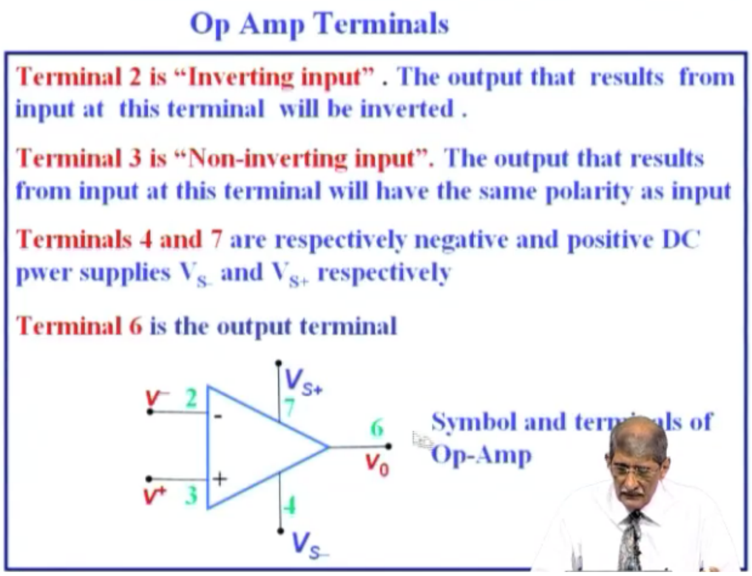

There are several terminals. The ideal one or the most important terminals are, I have marked it as 2, 3, 4, 6 and 7. 1, 5, etc or other terminals, which I am not showing. Terminal 2 is inverting input. The output that results from the input at this point will be of offset polarity. For example, if I have +1, there will be -1 here. Terminal 3 is non-inverting input, the output that results from this has same polarity. If I apply +1 here, it + voltage here with an amplification.

4 and 7 are the supply voltages. You apply a + voltage here, +10 volts, -10 volts nominally or +5 volts and – 5 volts nominally, which supplies the power required for the op amp. Here you apply your signal. The signal indicates the op-amp can DC and AC, that is what you mean saying direct coupled amplifier. So output terminal is V0 here. There is always a ground point somewhere here that I will not show here with respect to which you may apply the voltages and measure the voltages.

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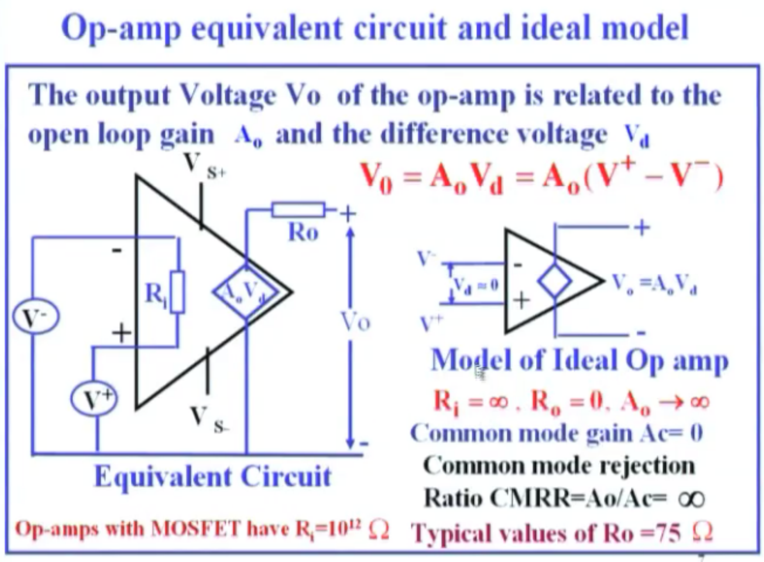

Equivalent circuit and ideal model, the output voltage V0 of the op amp is related to the open loop gain or the amplifier gain A0 and the difference voltage Vd. This is an inverting terminal. This is a non-inverting terminal. If you apply V+ and V-, the difference is V+ -V-. You will get an output voltage across these terminals, you will get the output voltage, which is actually difference between the 2, that Vd = V+ - V- into the differential gain of this amplifier that is V0.

Now when you use it in circuit, one have to remember that A0 is very large. Ideal equivalent of this is amplifier or not, output resistance is very, very small in these devices, maybe 50 to 60 ohms or even lower. I am putting it 0 here. So the output is an ideal voltage source whose value is V0 = A0*Vd. Now A0 if it is very, very large, for a finite V0, if A0 is very, very large, Vd will be very, very small.

What we are telling is you will get a finite output voltage from this amplifier with very, very small voltage across the 2 terminals. So for all simplified calculations, one can always take this difference to be negligible, that is there is a finite voltage, so that there is output voltage coming, but that is negligible for making simple analysis. Strictly speaking, you have to take this R input, which is very high. You have to take into account the difference between the 2 voltages here.

But as you see, it simplifies very much in all the op-amp circuits. Model for the ideal op-amp is input resistance is infinite, output resistance is 0, ideal voltage source A0 the gain V0 divided by this Vd that is infinite, tending to infinite. Then there is 1 more factor. So A0 is actually the differential gain, which is very large. Now the common mode gain, supposing I apply same voltage to these 2 terminals V+ and V- and apply voltage, ideally you must get 0 voltage.

In practice, we will have some small voltage. So that if I say Ac, Vc is the common voltage. I will get an output voltage V0C. So V0C/VC is a common mode gain. A0 is the differential gain. A0 divided by common mode gain AC is a common mode rejection ratio, which has got a very, very large 1000 or even more, ideally infinite. A0 is a differential gain. Ac is the common mode gain. So supposing there is 0.5 volts difference in the voltage and there is a noise signal of 0.1 volt here and 0.1 volt here, which is common, that noise signal will not be amplified.

Only the difference signal will be amplified. This is the greatest merit of the op amp amplifier that is whatever background signal is present, is eliminated because the common mode gain is ideally 0 or very small. In practice, the op amp with MOSFET, when you use MOSFET amplifiers inside this, they have RI of 10 to power 12 ohms, which is very, very high. Even if you have 1 volt input, it is 10 to power of -12 amperes, which is picoamperes.

So with that understanding, we will proceed. We take this voltage negligible and gain as infinite.

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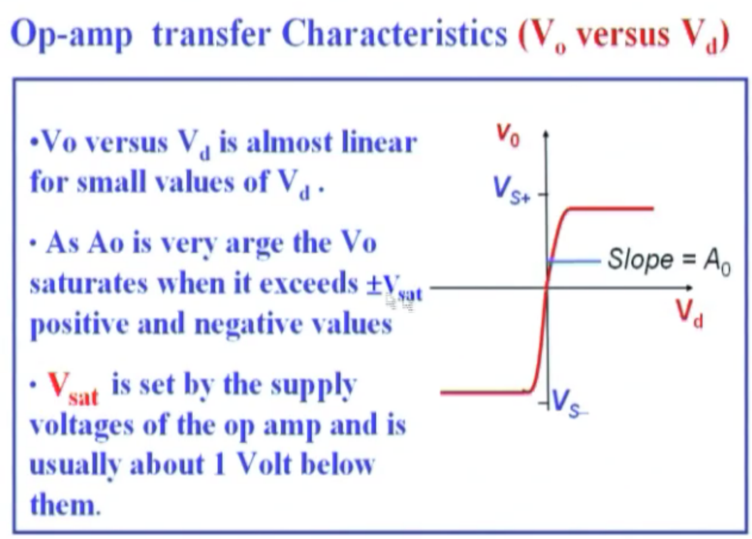

Now the op-amp transfer characteristics, V0 versus Vd. Ideally if A0 is infinite, this will go vertically up there, but there is a finite slope, which is very steep telling you that A0 will be Vi and as I pointed out in the case of amplifier. When the output voltage approaches that of the supply voltage Vs+, it will no longer increase beyond that. Ideally when this becomes equal to Vs+, it stops increasing. That is the saturation point, as in the case of amplifier that I pointed out.

Since there are two supplies Vs+ and V-, you will have two saturation points at Vs+ and Vs-, but in practice it will not go up to Vs+. It will be less by about a volt because there are other drops, which are present within the op-amp itself. So as a result, you can apply the signal voltage between which will be useful across the two terminal V+ and V- with just about 20-30 millivolts at the most here. By the time, it will go to infinite.

So this will be the slope into A0 will be the output voltage. That is the transfer characteristics and we will see now what one has to guarantee that the differential voltage appearing across the two terminals here is very, very small.

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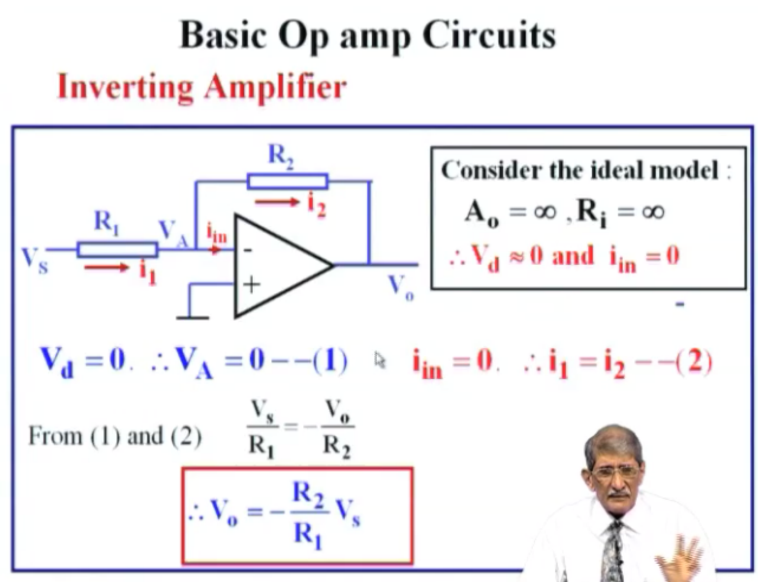

That is done taken care of very precisely with all the op-amp circuits with the connect external resistors. The entire gain, this is open loop gain that you are talking of A0, nothing is connected, very difficult to control. The small delta V here, it will take the transistor into the saturation op-amp saturation. So one of the very useful applications is a finite gain, inverting amplifier. What is meaning of inverting amplifier.

If I have + voltage here at the input, you get – output and it is amplifying, so the output V0 will be more than the Vs signal. So you can see the simplified analysis taking the ideal op-amp is the non-inverting terminal is connected to ground. That means the potential here is 0. As we already pointed out, you assume that in ideal case, the difference between the two terminals is very, very small, so we neglect that compared to the other voltage.

So if that is neglected, the potential here at this inverting terminal is also 0. If that is 0, so we make all through these assumptions simplified, more involved discussions you can make, you will arrive back into the same conclusion when the A0 is very large. This is the assumption. Input current is 0, input voltage 0, input resistance is high, therefore input current is 0. So all the current path is from Vs through this resistor to this output. So I1 = I2. What is the current I1? I1 = Vs –Va, Va is 0 because this is 0. Vs-Va divided by R1. That is Vs divided by R1 is I1 on the left hand side here and that is equal to this current here.

That current is 0 – V0/R2. 0-V0 is –V0/R2 is the current in that direction. So equating the 2, Vs/R1 = V0/R2-. Therefore, V0 = Vs x R2/R1-. So the gain of this amplifier is actually negative and the output is negative and the magnitude is R2/R1, I can get 0.5 volts input if I have, here the input will be very, very small. So if I have 0.5, if the gain is 10, I will have 5 volts output. Given that, ensure that the output power supply voltage for that should be more than 5 volts.

If the power supply voltage is 3 volts, the output voltage is saturated at 3 volts, so you will have clipping. This is an inverting amplifier.

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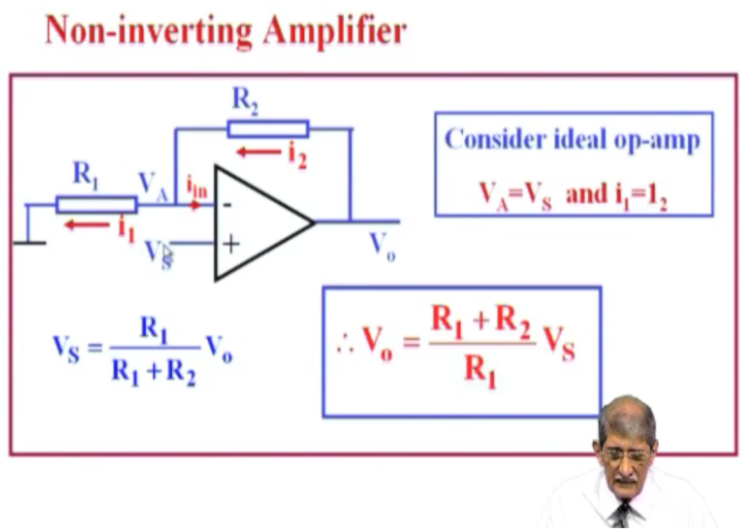

Now instead of grounding the non-inverting terminal, let us do one thing. Let us apply signal to the + terminal, which is non-inverting terminal and connect the resistor between like this, ground, R1 and R2. If you do that, now you can see, this VFS, the assumption is that the gain is infinite, voltage difference here between the two terminals is negligible. Therefore, the voltage here is Vs VA = VFS almost, strictly speaking this will be slightly different, because there is a difference in voltage.

But for all practical purposes, I can take VA = VFS, therefore, there is no input current here, the current flows from V0 through this to this to ground that is path for current is external circuit. So what is the voltage VA. VA = VFS that is equal to V0/R1 + R2 x R1. Because this is a potential divider. V0 gets divided between R2 and R1 and this output voltage VA with respect to this ground is V0 x R1/R1 + R2 and VA = VFS. Vs = R1/R1 + R2. So V0 = Vs x R1 + R2/R1.

In other words, V0 is 1 + R2/R1 x VFS. So if R2/R1 = 2, it will be 1 + 2, that is 3 x VFS. I will have a gain of 3 for this amplifier and polarity V0 will be same as VFS. If it is plus, it is plus. In fact, this particular type of amplifier is very commonly used in Wien bridge oscillator to realize the amplifier of gain 3. You have RC-RC combination and amplifier of gain 3, you can precisely get this gain 3 by the Wien bridge oscillator by choosing this ratio as 3. This is very commonly used.

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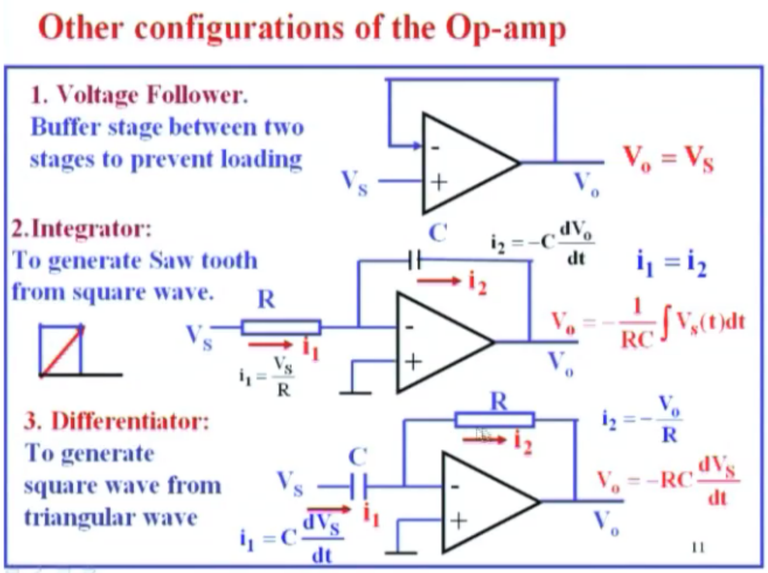

Now other configurations of the op-amp, voltage follower. What is the meaning of that? The output = input, no voltage gain, how is it obtained, connect this output terminal to this inverting terminal. Since Vs is applied to the plus terminal, voltage drop across these 2 is negligible. So here also that V0 = VFS. VFS is here. VFS is present in this point. Therefore, V0 = VFS. Voltage gain is not there. What is the use of this. All that you get is you can use it as a buffer.

If I connect this to the previous output stage of an amplifier, because this has very high input resistance. It will not draw any current. So I can connect this in between one stage amplifier and next stage of signal conditioning circuit or a measuring circuit, so that the output resistance here is small, input resistance is large. This does not load the previous circuit and since output resistance is practically 0, entire voltage is available for these circuit or the nest measuring device.

So this is a buffer. Where you commonly use. Then the integrator. Instead of using a resistor in this portion, inverting amplifier, I have connected a capacitor here. We have seen that current I1 = current I2. Now, I1 is ES/R, I2 will be, this will be useful only when there is a time varying signal because current through a capacitor is Cd/dT. Only if there is voltage change, then only it can allow the current to flow. So I2 = -C x dV0/dT. So these 2 are equal.

So therefore Vs/R = -C x dV0/dT integrating V0 = -1/Rc x that Vs x dT, which means that if I have a signal input here, what I get there the output is integral of the signal, very useful to generate saw-tooth from a square view. I have shown it here. If there is a wave shape like this, square wave for one square I have shown, integral of that is linear. So it is a saw-tooth, it will come down, so you can keep on increasing or decreasing like that, so integrator.

If I interchange the capacitor, put it here and a resistor here. By the same way, you can analyze and see that I1 is CdVs/dT, because this is 0. Voltage drop across the capacitor is VFS. CdVs/dT is the I1 and I2 is –V0/R, because this is 0, this is V0. V0/R is current I2, equating –V0/R and CdVs/dT, we get V0 = -RC x dVs/dT, which means that the output will be differential of an input. In other words, if I have a saw-tooth wave shape, I can differentiate it and get a square wave.

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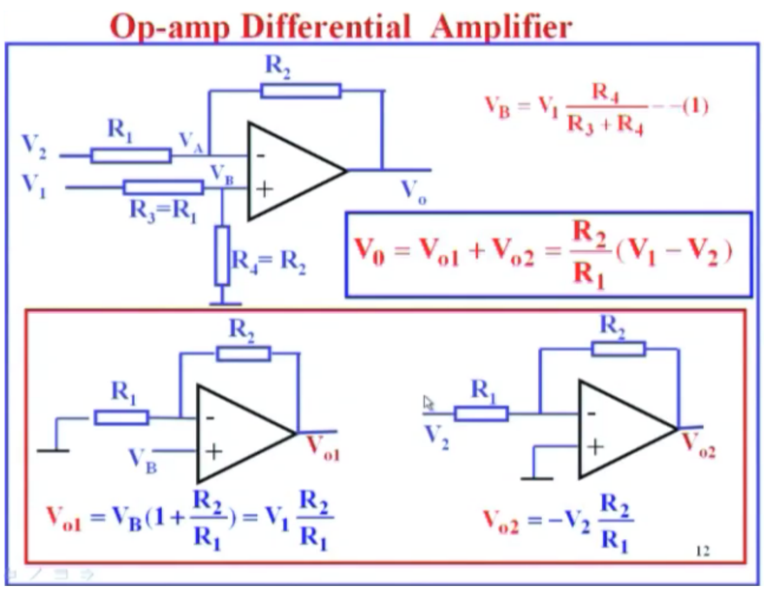

Now let us take a look at differential amplifier using an op-amp. Here you can see that V1 is applied to the non-inverting terminal to this resistor and V2 is applied through this inverting terminal to the output like that. So what we want to find is what will be the output voltage for this case. V1 and V2 are applied. You can analyze this very simply by considering this circuit as superposition of these two circuits.

In this portion, what I did, I have found out what is the voltage Vb is and take that Vb as the input voltage to the op-amp and consider the V2 as 0. I am considering only the effect of his V1 to find out what is V0 with V1 alone. Next what we will do will be ground this point, consider the effect of V2 alone, here. If I ground this point as well as grounding this Vb, ground this point. Consider how much output I will get with V2 alone.

So V0 will be V01, which you get considering the effect of Vb alone and considering V2 as 0, what is the output + the effect of this circuit where V1 is considered 0 and take the output V02 with V2 present like this. Now let us see what it is. What is Vb. Nothing else is coming here. Vb is equal to V1/R3 + R4 x R4. I have written R3, R4 to distinguish between the 2, but in reality R3 is made equal to R1 and R4 is made equal to R2. Therefore, Vb will be V1 x R2/R1+R2.

Now if I have Vb here applied, this is an inverting amplifier. The V01 due to this inverting amplifier will be Vb x 1+R2/R1. This is what we saw just now, here. If there is a signal, V0 = Vs x R1+R2/R1 or 1+R2/R1. So V1 = Vb x 1+R2/R1. Now Vb = we saw, if this is R1 and this is R2 that is = R2/R1+R2. So R1+R2 in the numerator cancels with the R1+R2 in the denominator and we get R2/R1. So for this amplifier, the gain is V1 x R2/R1.

That goes up because Vb is now applied through this resistor. So you get V01 = V1 x R1. Vb is now simplified using this relation, so V01 is related to V1/R2/R1 if other signal is not there in this amplifier. Now V02 for this case is very simple. I ground this point, find out how much is V02. This is the inverting amplifier. V02 is V2 x R2/R1 with a negative sign. V02 is V2 x – R2/R1*V2. So as I mentioned earlier, the total voltage output here will be this + that.

That is V0 = V01, which V1 x R2/R1 +V02, which is –V2 x R2/R1, so that is R2/R1 x V1-V2. So ultimately, what we conclude is this is an amplifier, which uses an output = the difference between the 2, V1-V2. If V1 is connected to this + terminal, V2 is connected to – terminal, the output is positive and the gain = R2/R1. Precisely, you must have R2/R1 and R2/R1 here. Now you can see that the ratios and all are controlled.

The gain is controlled by these 2 resistors R2 and R1 and both of them must be having R2/R1 exactly same. Now, you can modify the circuit. The benefit of the circuit, of course, it is a high input resistance and output is exactly difference between the 2. You can get still higher input impedance and another additional gain by modifying the circuit, which you call it as usually instrumentation amplifier.

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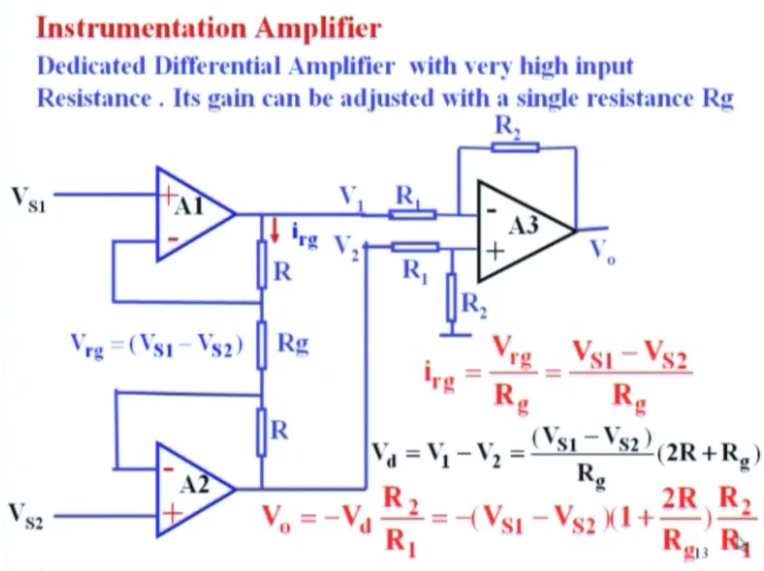

In instrumentation amplifier, you want to increase the gain further. You want to have very high input resistance. Already you have got very high input resistance there. Now, if I have 2 of them connected like this between the Vs1 and Vs2 very large input resistance you will get and let us see how this gain can be increased further. Notice in the previous case, it is R2/R1 x V1-V2. So in this case, the gain will, the output voltage will be Vs1-Vs2 x R2/R1 as in the previous case, multiplied by a factor 2R/Rg.

That is obtained by connecting this like this. This is a simple circuit. There is no problem at all. So V1-V2, if I take V1-V2, then this will turn into – sign. V1-V2 x R2/R1 will be V0. How much is V1-V2 is we have to find out in terms of Vs1 and Vs2. So you can see here, this looks difficult, but very simple. This is the difference in amplifier which we have put in the previous slide that is V1-V2 and that is amplified by factor R2/R1 with a negative sign.

What is V1-V2, we have to find out, that is this difference. That is output voltage here – this voltage. What is output voltage here, that is drop across Rg+drop across 2 resistors. Drop across Rg is, what is the voltage here, same as that Vs1, because drop across the 2 remnants is negligibly small. So this is Vs1 and this voltage is at Vs2. The difference between the 2 is negligible. So this is Vs2, this is Vs1, difference is Vs1-Vs2.

That is the voltage that is present here and what is the current through this Rg. Current through the Rg is Vs1-Vs2/Rg. So the total voltage V1-V2 is Vs1-Vs2 + Vs1-Vs2/Rg x R+R, that is 2R. 2R x Vs1-Vs2/Rg, 2R x the current that Vs1-Vs2/Rg + Vs1-Vs2 that is the difference. That difference voltage, that is this quantity I just put again here, the difference voltage x R2/R1. So you can see, the output voltage in this case compared to previous case.

Previous case, it was amplified only by R2/R1 on the signal. Now, there is an additional factor, which comes up as 2R/Rg again through this value of Rg, so that I can increase the gain of this amplifier. So the differential amplifier with this arrangement is often used as an instrumentation amplifier with very high gain because it is R2/R1 into a factor, which can be controlled by this Rg and very high input resistance.

Because there are 2 inputs are coming here between these 2 terminals, input of this op-amp, this op-amp + this quantity. So you get very high gain and the usefulness of this is extremely high input impedance.

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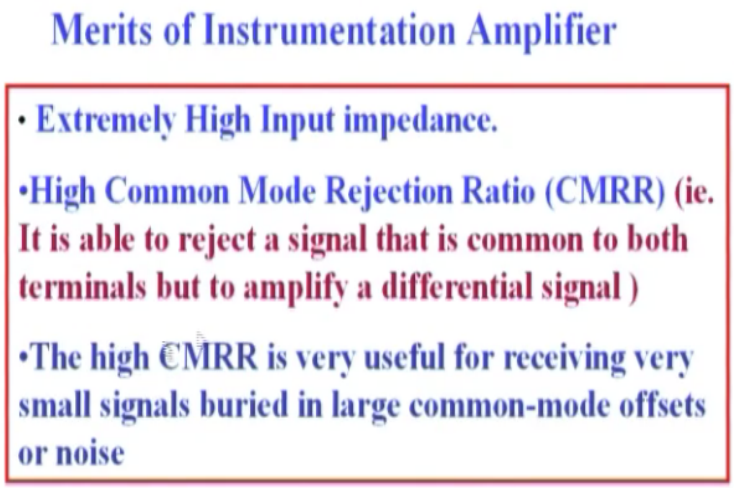

This is called instrumentation amplifier. So the difference between the instrumentation amplifier and ordinary differential amplifier is additional stage here. Extremely high input impedance, high common mode rejection ratio, that is it is able to reject the signal that is common to both terminals, but amplify a differential amplifier. So it amplifies the difference in voltage with very high gain and the difference of the common mode gain is very, very small. It rejects that.

The high common mode acceleration is very useful for receiving very small signals buried in large common mode effect offsets or noise. So as I pointed out already, if there is noise signal coming between the two input terminals, that is not going to be amplified because common mode gain is very small, but the difference between the voltages, which may be even small signal, that will be amplified quite a bit because the gain is large.

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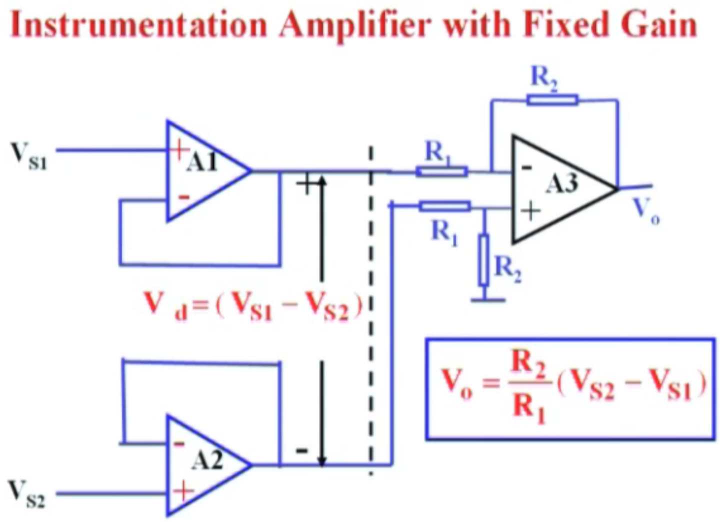

Now you can choose the different that you are opting noise, I do not want that very high gain. Because if I am getting already very high gain by means of this R2/R1, I had want only a fixed gain. I can change this. In this case, I can change the gain by changing Rg, but if I remove this Rg, then use it like this. I remove the Rg, use this as unity gain amplifier, whatever you get here the Vd here is Vs1-Vs2. How is that possible. Vs1 is same as here Vs1.

Vs2 is same as Vs2 here because of unity gain. So Vs1-Vs2 is the input voltage and from here onwards this is the differential amplifier, which use R2-R1. There will be a negative sign coming in this particular circuit, because you put it Vs1-Vs2. Since I have put Vs2-Vs1, there is no negative sign. Because you take this as + - that. if I put Vs1-Vs2, I would have got a negative sign here as in the previous case.

This is another version of the instrumentation amplifier with gain not so high, but it gives very high input resistance and very high common mode rejection ratio.

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Signal conditioning for Microsystems

Analog to Digital Converter

(A/D converter or ADC)

- Output signals of most physical systems (eg Sensors) are Analog ie continuous functions of time .
- Need to convert them into binary form to enable processing in the digital domain to achieve higher efficiency and reliability
- ADC is the circuit which performs this conversion and provides an output that digitally represents the input analog voltage level
- The input voltage is sampled at intervals T_S and output is digital in binary form

Now we will come to some of the signal conditioning circuits for Microsystems. Today, we will focus only one such circuit or device, which is popularly known as analog to digital converter or A-D converter or ADC. Here why do we need analog to digital conversion. The output signal of most physical systems such as pressure sensor, acceleration sensor, etc. are analog. When you say it is analog, that means that the signal is continuously varying with time.

At each instant of time, the signal is present. That is analog. You can see the sine wave is an analog signal. Now we need to convert them into binary form to enable processing in the digital domain and processing in the digital domain enables you to achieve higher efficiency and higher reliability, less of noise and you can process it with great efficiency. These are some of the advantages of that digital signal processing, much more efficient than the analog, much more simple.

You can have similar type of circuits to process the signal and making the integrated circuits for digital circuit is much simpler, all those advantages are there. So today all the processing is done in the digital domain and therefore you require to convert the analog signal into binary form, that is ones and zeros. It is present for certain duration with one, certain other duration with zero. So it is a combination of these plasma sets and etc.

So ADC or analog to digital converter is a circuit which performs this conversion as the name itself indicates. Now in this type of ADC, in the ADC circuit the input voltage is sampled at regular interval TFS, and output is digital in binary form. It is sampled for example there is a sine wave, you take that particular signal at T1 and convert into digital form and take it at T2 after interval TFS, convert that into digital form and the entire output of the ADC is a sequence of binary numbers.

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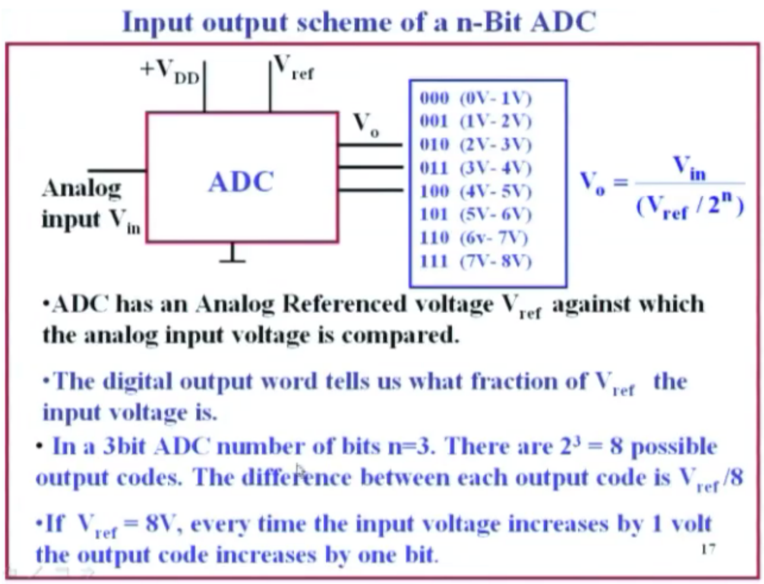

So the input output scheme of a n-bit ADC, now for example, what is the being of n-bit. If there are 3 pulses to decide 1 word, then this is called 3-bit. For example, I can write a number, a voltage 0 as 000. There are 3-bits are used, each one is a 1 pulse, here all the pulse are 0. Second one, if you take 001 pulse is 0, pulse is 0, third pulse is 1 that is high, the pulse is present here. Now in a digital form 001 is 1 so it may represent 1 volt, 010 in a digital form is 2, 011 is.

I am sure you have studied in some place rather so I am just saying that. So this is the n-bit, 3 binary numbers are used here, 3 bits are used to realize the number. The first digit is, in each case you multiply by 2 to the power of something. Here it is 1 x 2 to the power of 0, that is 1. Here this is 0 x 2 to the power of 0, that is 0. 1 is 1 x 2 to the power of 1 that is 2. That is why this number is 2. Here this is 1 x 2 to the power of 0 that is 1. This middle number is 1 x 2 to the power of 1 that is 2, 2+1 is 3. So here 1 x 2 to the power of 2 that is 4, 0 x 2 to the power of 0, this rating factor is 00 this is 4.

So this is 4, this is 1 x 2 to the power of 1, this is 1, so 4+1 is 5. So these numbers indicates 0, 1, 2, 3, 4, 5, 6, then 7. Now the analog ADC has analog reference to voltages V-reference against which the analog input voltage is compared. You compare the input voltage with this reference. Digital output word tells us what fraction of the reference the input voltage is. A 3-bit, to understand it a 3-bit ADC analog digital converter number of bits are is equal to 3, for example here, number of bits is 3, it is a 3-bit ADC where n, if it is a n-bit number of bits is n.

For example if it is 4 bits, then 4 numbers here, that is n is equal to 4. Now in the 3-bit ADC there are 2 to the power of 3, that is 8 possible output codes, like this. Here you can see, I have 1, 2, 3, 4, 5, 6, 7, 8 codes are there, 000, 001, 010, all these things. Now these are the digital representation. So you can have 8 possible output codes. In the case of 4 bits, 2 to the power of 4 that is 16 possible codes, 0000, 0001 like that. You will have 16 possible output codes.

Now V reference, if it is, there are 8 possible outputs that I have shown, the difference between each output code is V reference by 8. See for example this code 00 between the voltage, between the 00 code and 001 is whatever reference is there divided by 8, because n-bit. So there are 8 division, 8 such codes are there, the difference between the 2 codes E = V-reference/8, which means if V-reference is 8 volts the difference between the code 000 and 001 is 8/8 that is 1.

V-reference by 8, see 8 volts/2 to the power 8 that is 8, so that is 1 volt. So each number when the code goes up by 1 number that would correspond to an input voltage increase of 1 volt. Now the 00 in the ADC would correspond to analog voltage of between 0 and 1, anywhere between 0 and 1. 001 would correspond anywhere between 1 and2. So you can see the voltage has gone up from 0 to 1, 1 to 2, 2 to 3, 3 to 4, but between 000 and 001 the output voltage varies remains at 000.

When the input voltage has varied from 0 to 1 till that point output was 000, when the input was 1 output has changes to 1, 001. Similarly output remains at 001 till input voltage varies from 1 to 2. When it becomes 2 this becomes 010 that correspond to 2 volts. This becomes clearer with this circuit.

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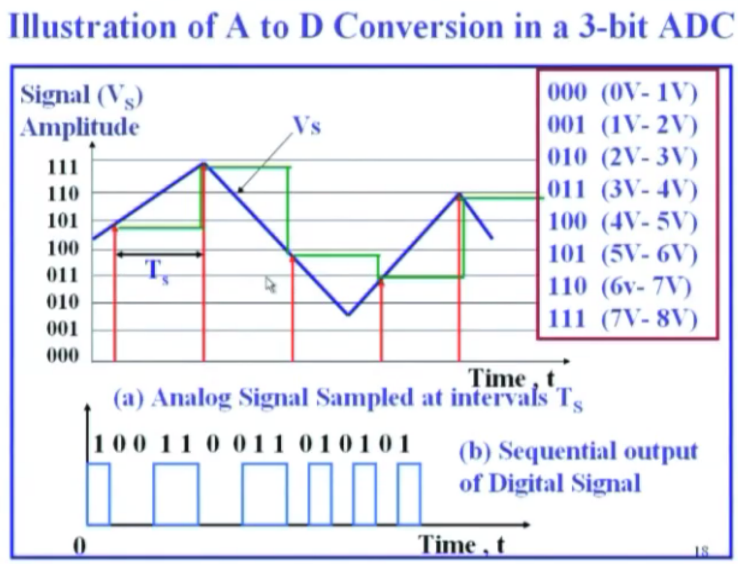

Now what I am showing you here is the conversion from analog voltage a triangular voltage like this with the ADC. With time the analog voltage varying like this. Now if I give this input to the analog to digital converter, now you see 001, 1, 2, 3, 4 all these things would correspond to correspondingly the digital voltage output. If all of them are said 001 is 0 to 1 volt. Here you can see I am sampling this voltage initially then after Ts, I am sampling, I am converting that into digital signal and sampling here converting into digital signal.

Now you can see at this point of time, the input is actually between 100 and 111 which means actually it is 4 volts, it is 4 and 5. So it is between 4 and 5, when it is between 4 and 5 the digital output will remain at 100, 100 will give 4 and 5 input. You have to see corresponding to this analog what is the previous digital, that is 100. Now what will happen is it will sample here, generate a digital output which is 100. You can put the output sequence as 100, a pulse 1, nothing these 3, this 3 0, this 100 pulse corresponding to that.

Then after time TFS it is sampling here. So here what is the voltage, it is between 110 and 111 actually it is 5 volts, this will be 5 volt here. This is 110 and 111 between that 6 volts that is 6 volts correspond to 110, 6 volts with the 1. So 6 volts will be the digital output in the corresponding to input voltage 6 volts, so long as the input is between the 6 and 7, the output will be 110. So it is between 6 and 7 the output will be 110.

So you can see it generates 110. So pulse rate is 2 there are 2 pulses are there 110. So like that it goes on repeating. For example here it is between 100 and 111 the signal which will actually correspond to 11, 011 that is 3 volts, so it will correspond to that. So the pulse here will generate a signal which is 011, so like that it will go on. This sequential output will be representing the how much the digital output corresponding to this here.

Next is how much is corresponding to this that is this 1. Next is how much is corresponding to this that is 011, that is corresponding to this 010, corresponding to this that is 0101, 101 you see 101. Now finally the digital signal will be converted to analog signal what happens is between this signal and this signal the output reveals same as this value, analog output. That is if it was 5 volts 100, if it is 4 volts it will remain so, the output voltage will be finally.

When you convert the digital output to the analog output using a D to A converter, the output will be like this. Here actually whatever was digital signal input was this blue has become green like that, because the voltage remains as this value till the next voltage comes in. So that is the idea of that. So if I make it sampling closer and closer, this output will be closer to this particular input signal. So this is the idea of the analog to digital converter.

You use A to D converter for signal processing, D to A converter for converting back to analog that is ultimately you need analog signal to do some work. With that I close down today's discussion. We will be gone with further on these aspects in my next lecture. Thank you.